Single String Integration Test of the High Voltage Hall Accelerator System

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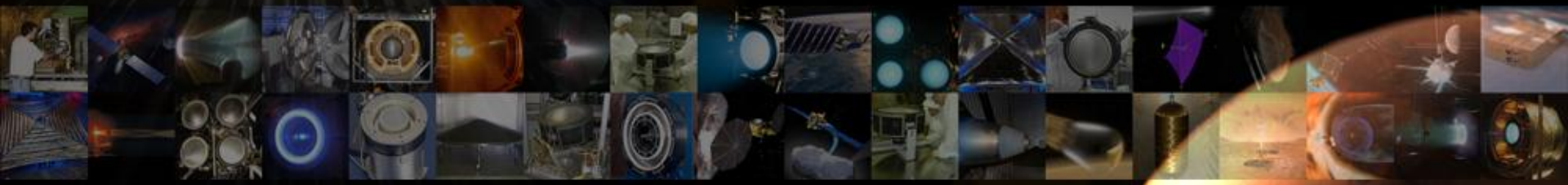

60th JANNAF Propulsion Meeting
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High Voltage Hall Accelerator (HiVHAc)

- **Hall Thrusters have been successfully used in EP systems**
  - **Flying continuously since the 1970's due to the inherent system simplicity (low cost), reliability, and reduced mass relative to gridded ion thruster systems**
- **In Space Propulsion Technology project study in 2004**
  - **Directed Hall thruster development towards lower-power (Discovery class) missions – 0.3 to 3.5 kW**
  - **Study concluded need for improvements with respect to: *Specific impulse*, *Throttle-ability*, and *Life***
- **<u>HiVHAc Task Objectives:</u>**
  - **Develop and demonstrate low-power, long-life Hall thruster technology to enable cost effective EP for Discovery-class missions**
  - **Advance the TRL level of potential power processing units and xenon feed systems to integrate with the HiVHAc thruster**
- **<u>Approach:</u>**
  - **Develop HiVHAc thruster with commercial Hall thruster manufacturer to leverage production capability, minimize non-recurring cost, and to assure supplier**

A HiVHAc system will offer superior mission performance at reduced cost

A Hall EP System is a Lower Cost Option when Compared to a Gridded-Ion EP system

Thruster	Config.	Cost Δ$M
NEXT 1st User	1+1	26.5
NEXT nth User	1+1	7.0
Hall 1st User	1+1	6.5
Hall nth User	1+1	0.5
Chemical Biopropellant	1+0	Baseline

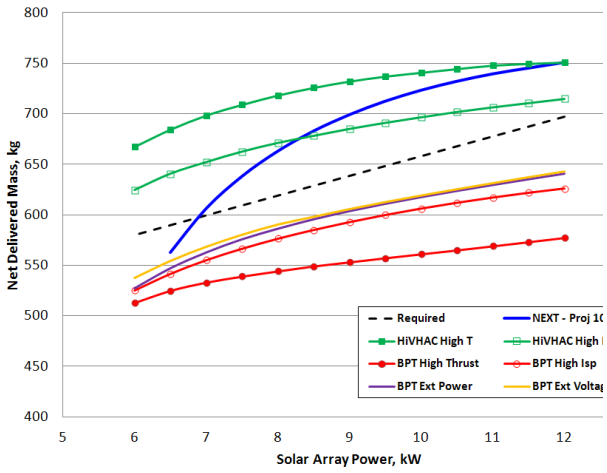
	Thruster	Config.	Cost Δ$M
First User	NEXT	1+0	-8.1
		1+1	Baseline
		2+1	6.5
	Hall	1+0	-25.2
		1+1	-20.0
		2+1	-15.0
Nth User	NEXT	1+1	-19.6
	Hall	1+1	-26.0

A Hall EP system will enable a wide range of Discovery class missions and will also enable a far greater science return that chemical propulsion system alternatives.[1]

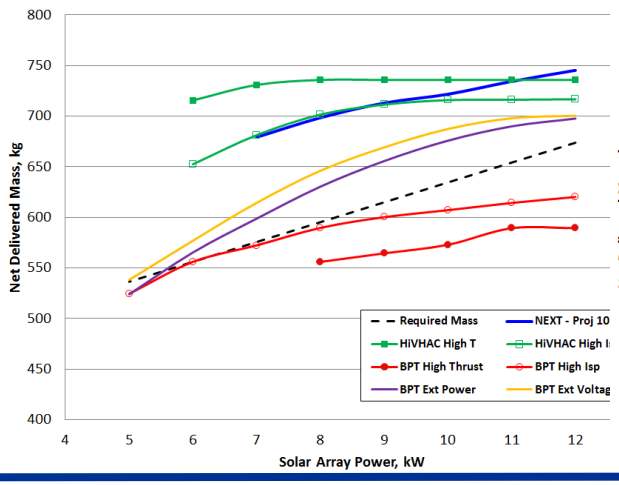
1. Dankanich, et. al., " Electric Propulsion Mission Viability with the Discovery Class Cost Cap," AIAA-2010-6676.

The HiVHAc EDU Thruster Performance is Capable of Completing Four Discovery and Two New Frontier DRMs

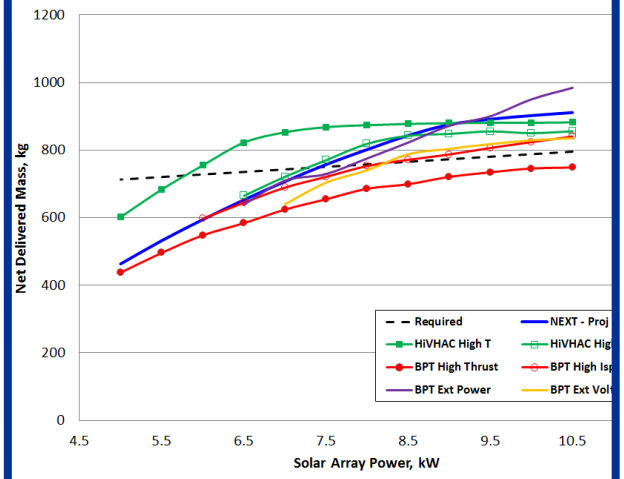
DAWN Mission



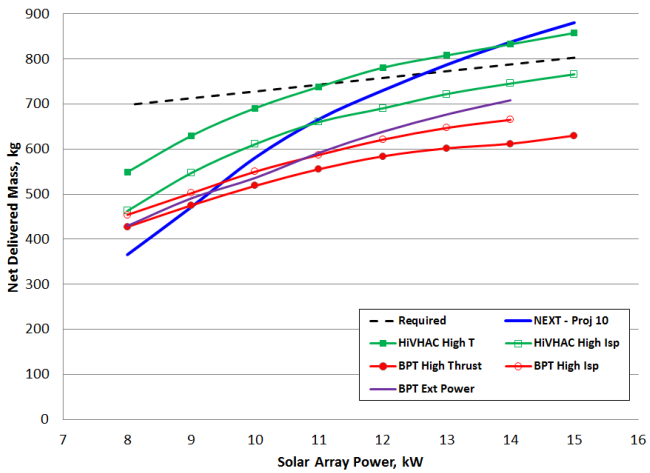
Kopff Rendezvous Mission



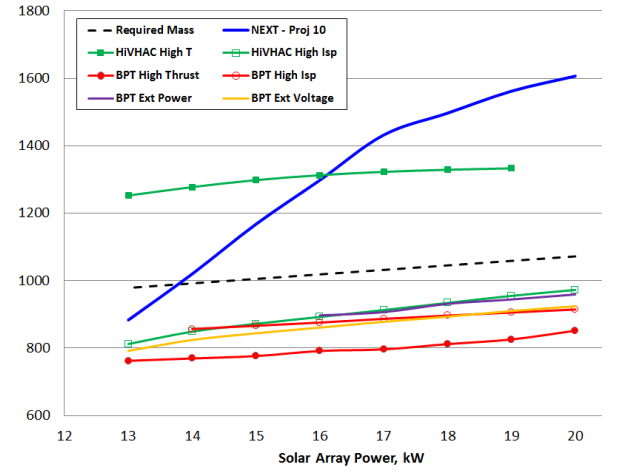
Nereus Sample Return Mission



NEARER Sample Return Mission



Wirtanen CSSR

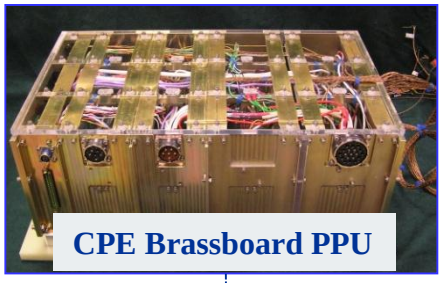


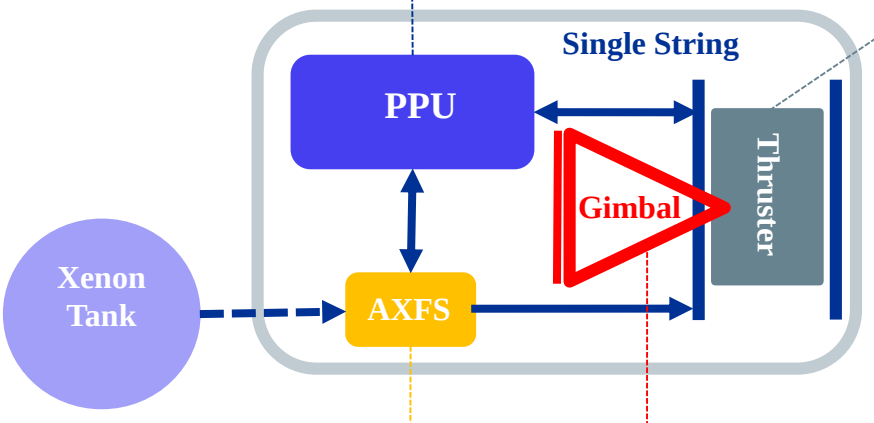
C-G CSSR

Results from Study conducted by John Dankanich comparing performance of HIVHAC to BPT-4000 Variants, SPT-140, and NEXT. Results will be presented at an upcoming conference

HiVHAc System Layout

- The HiVHAc project has leveraged OCT SBIR funding to advance the HiVHAc thruster system readiness
- Extensive atmospheric and vacuum testing of the Colorado Power Electronics (CPE) brassboard PPU has been performed at NASA GRC
- NASA GRC plans to perform SDT and LDT testing of the CPE BB#2/EDU PPU with the HiVHAc EDU 2 thruster





- The HiVHAc engineering development unit (EDU) 2 thruster offers improved performance and mission benefits over SOA
- The HiVHAc EDU 2 thruster incorporates an in-situ self regulating discharge channel replacement mechanism

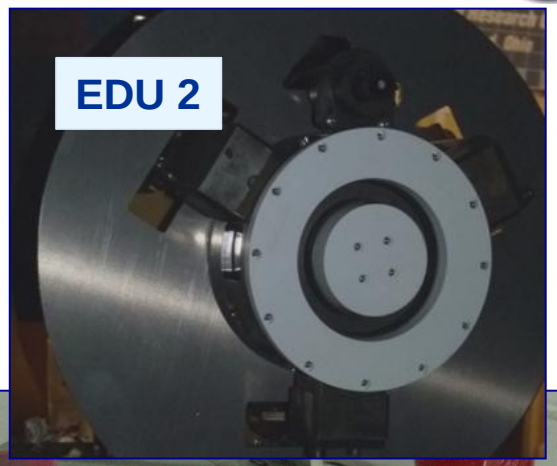
VACCO XFCM

Gimbal (derived from NEXT)

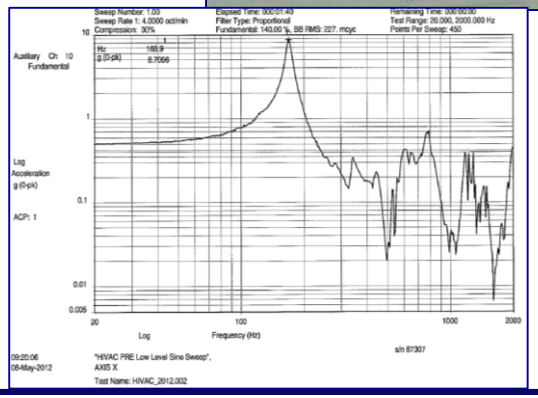
- The HiVHAc project has leveraged ISPT and DoD/USAF funding to mature the TRL level of a xenon feed system for HiVHAc
- A flight-qualified VACCO xenon flow control module (XFCM) was delivered to NASA GRC in June 2012 and will be integrated with the HiVHAc thruster SDT and LDT

HiVHAc EDU Design & Manufacturing Approach

- **HiVHAc EDU 2 Thruster design features include:**
  - Integrated magnetic structure
  - Low cost anode design
  - Heritage 6.35 mm hollow cathode
  - Low cost propellant isolator
  - Thermally efficient electromagnet design
  - Discharge channel replacement mechanism for life extension



- **EDU2 has completed a series of tests that include:**
  - ✓ Performance acceptance
  - ✓ Thermal characterization
  - ✓ Random vibration
  - ✓ Discharge channel replacement mechanism hot-fire actuation test



Power Processing Unit Options for HiVHAc

- The functional power requirements of a HiVHAc PPU are that it operates:
  - Power range 0.3 to 3.8 kW
  - Input voltage range 80 to 160 V
  - Output Voltage range 200 to 700 Vdc
  - Output current range 1.4 to 10 A

- Within NASA's small business innovative research (SBIR) program, there are three projects that are developing wide range discharge modules for integration with Hall thrusters
  - The highest maturity PPU developed under the SBIR program is the Colorado Power Electronics (CPE) PPU.
  - Other discharge modules/PPUs will continue to be evaluated for integration with Hall thrusters as warranted.

CPE Brassboard PPU Testing

- CPE Brassboard (BB) PPU has two high voltage discharge modules, keeper, two magnet, and heater modules (in a slice configuration).

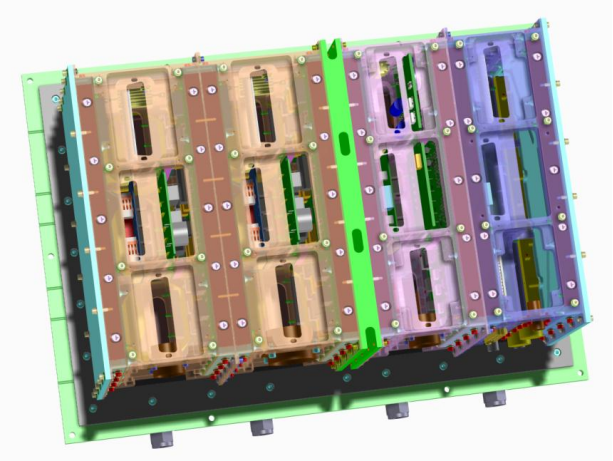
- The CPE BB PPU has accumulated over 1,500 hour vacuum burn in test @3.5 kW with a resistive load
  - A new vacuum facility, VF70, has been assembled for PPU testing.
  - VF70 is an independent vacuum facility located directly next to VF12.

- The CPE BB PPU has been used to power the thruster for all performance and thermal characterization tests,
  - It has accumulated another 500 hours of PPU operation with a thruster plasma load.

CPE Brassboard & Engineering Development Unit PPU Maturation

- Under a Phase II SBIR CPE is further developing and maturing the HiVHAc brassboard PPU design- The new barssboard unit is designated CPE BB 2 PPU

- Under the Phase II and Phase IIE SBIR efforts CPE will:
  - Design and build a refined brassboard PPU that will have the fit and form of a qual unit, delivery is expected in May of 2013
  - This unit will be subjected to thermal vacuum, structural, and extended duration vacuum tests at NASA Glenn- Findings from CPE BB 2 PPU test will be incorporated in the CPE EDU PPU build
  - Design and build an EDU PPU that will incorporate flight rated components, delivery expected in April of 2014

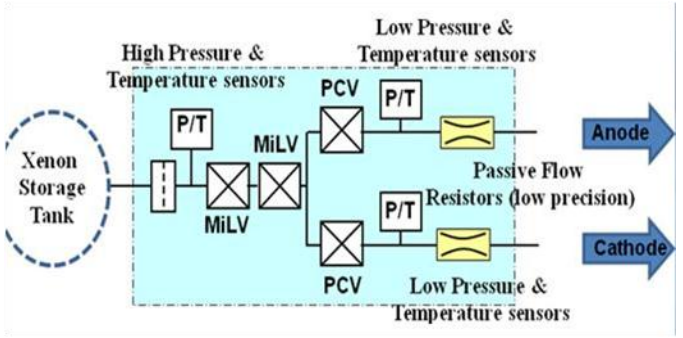


Xenon Flow System

- **NASA GRC and AFRL have acquired a VACCO Xenon Flow Control Module (XFCM) that is a low-cost, light-weight, and has low-power consumption XFS**

- **The XFCM is as a two channel electronic flow controller with a series redundancy to protect against leakage. It includes integral pressure and temperature sensors**

- **Demonstrated by test**
  - **Flow accuracy**
  - **Power consumption**
  - **Vibration environment**
  - **Shock environment**
  - **Thermal environment**
  - **Minimum and maximum inlet pressure operation.**



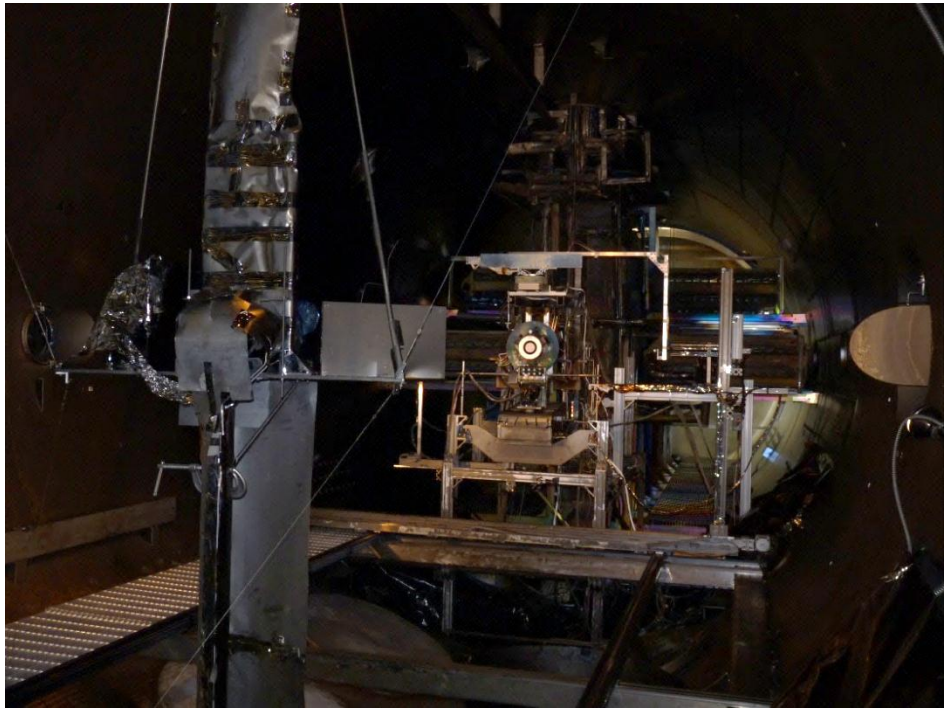
Inlet Pressure Range	10 to 3000 psia
Anode Flow Range	0 to 80 sccm Xenon
Cathode Flow Range	0 to 80 sccm Xenon
Flow Accuracy	±3% of Set Value (closed loop)
Lifetime	10 years, 7,300 cycles, 100% margin
Mass	1.25 kg
Size (W×H×D)	19.5 cm × 7 cm ×7.5 cm

Single String Integration HiVHAc Test Configuration in NASA Glenn Vacuum Facility 5

- **The primary objective of the single integration test in VF5 is to assess the performance of the HiVHAc thruster with the CPE BB PPU and VACCO XFCM**

- **<u>Additional objectives of the HiVHAc SSIT in VF5 include:</u>**
  - **Assess performance of HiVHAc EDU thruster in the lowest possible attainable background pressure environment and at elevated background pressure**
  - **Perform detailed thermal characterization of the HiVHAc thruster using thermocouple and IR camera (Aerospace Corp) measurements**
  - **Perform detailed near field polar maps of the ion beam**
  - **Measure plasma properties in the near field plume using AFRL high speed Langmuir probes (HSLP)**
  - **Perform far field plasma measurements using EXB, RPA, and Langmuir probes**
  - **Acquire HiVHAc thruster EDU VI characteristics to assess thruster stability at various operating thruster flow rates and magnet settings**
  - **Perform Fast Camera measurements to characterize thruster operating modes**
  - **Evaluate thruster performance at different cathode positions**

HiVHAc SSIT Test Setup in VF5

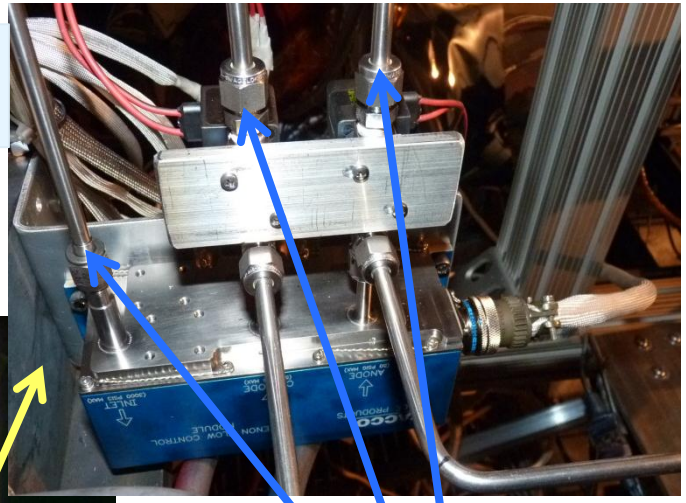


Single String Integration Test

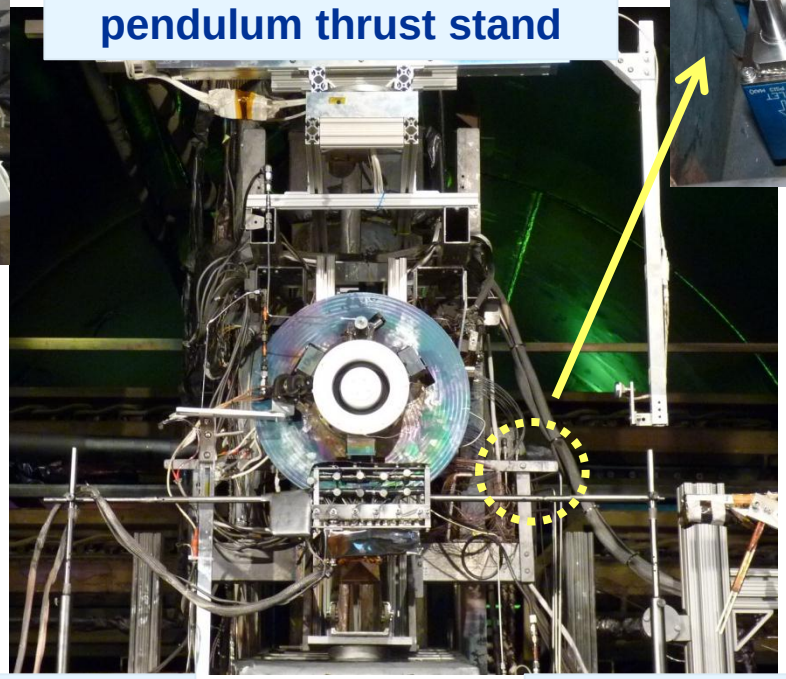
Configuration in NASA Glenn Vacuum Facility 5 – (p1 of 5)

CPE BB PPU outside VF5

VACCO XFCM inside VF5



HiVHAC mounted inside VF5 on inverted-pendulum thrust stand

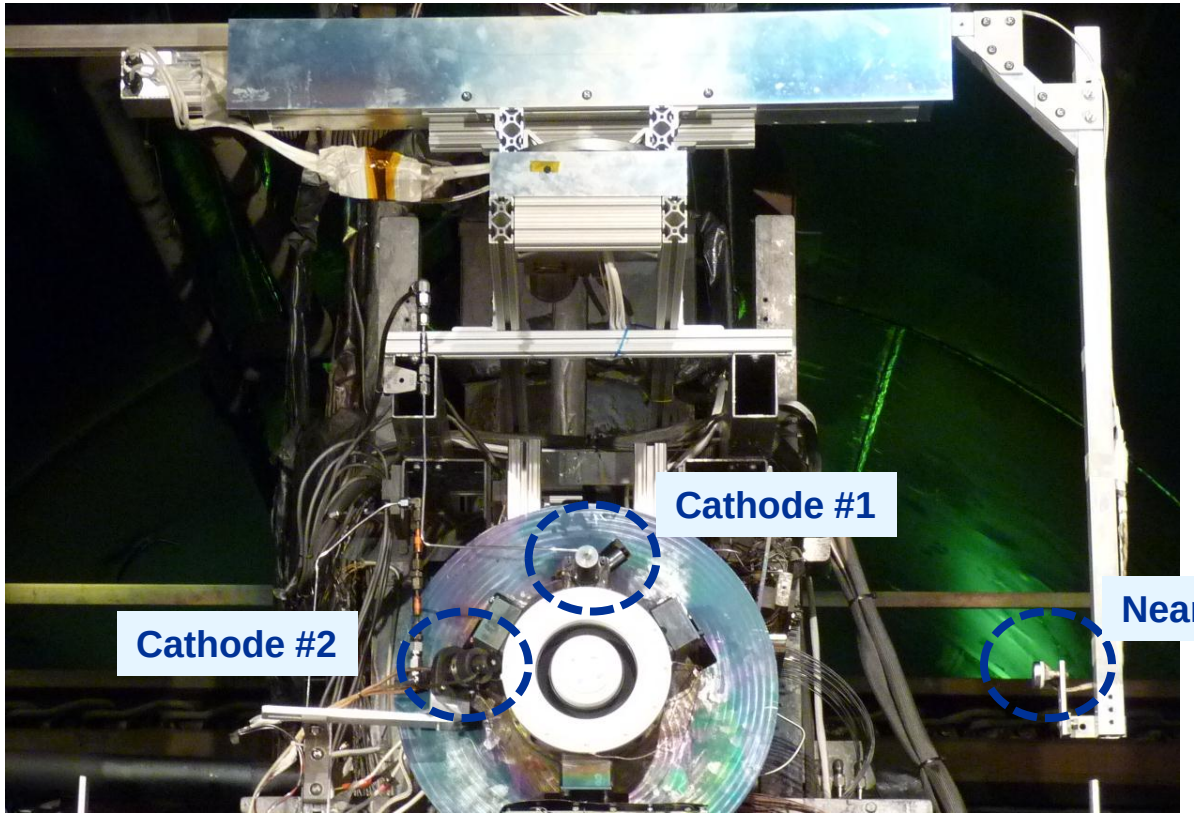


Laboratory power supplies for V-I test

MFCs that supply xenon to XFCM and Thruster

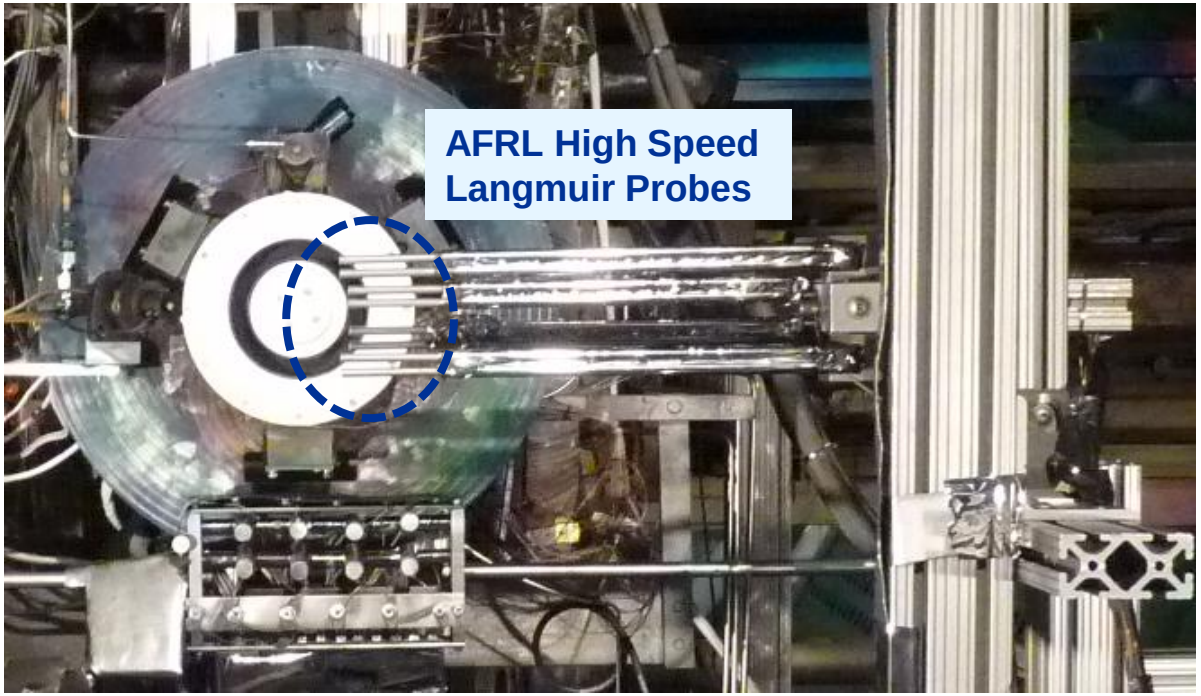
Single String Integration Test

Configuration in NASA Glenn Vacuum Facility 5 – (p2 of 5)



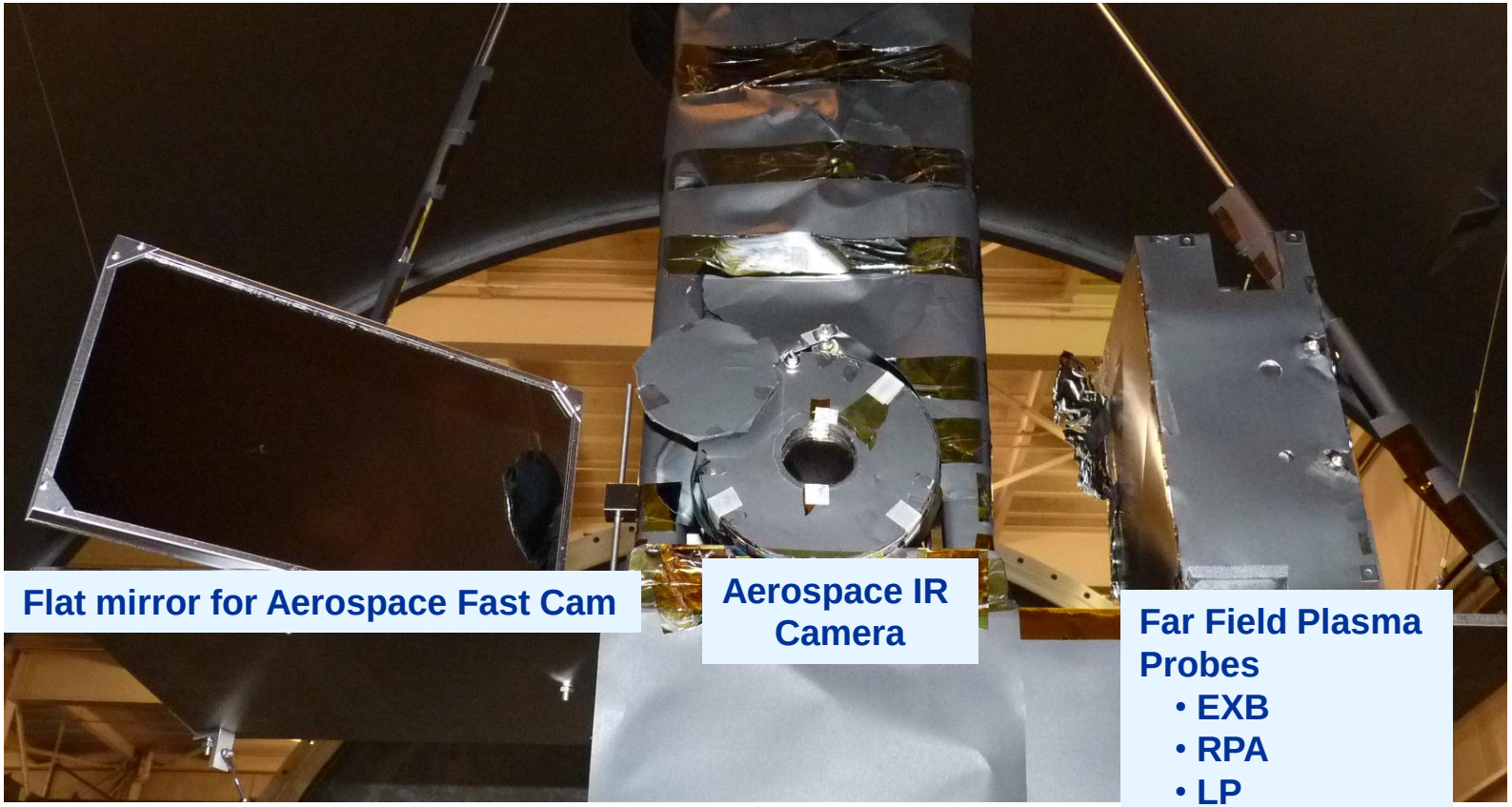
- Test configuration includes a stationary cathode (#1) and a movable cathode (#2)
- Plasma diagnostics includes a near-field Faraday probe (FP) that is situated on an arm that is anchored on rotary and axial stages

Single String Integration Test
Configuration in NASA Glenn Vacuum Facility 5 – (p3 of 5)



- **Plasma diagnostics includes AFRL high speed Langmuir probes (HSLP) that are situated on radial and axial stages**

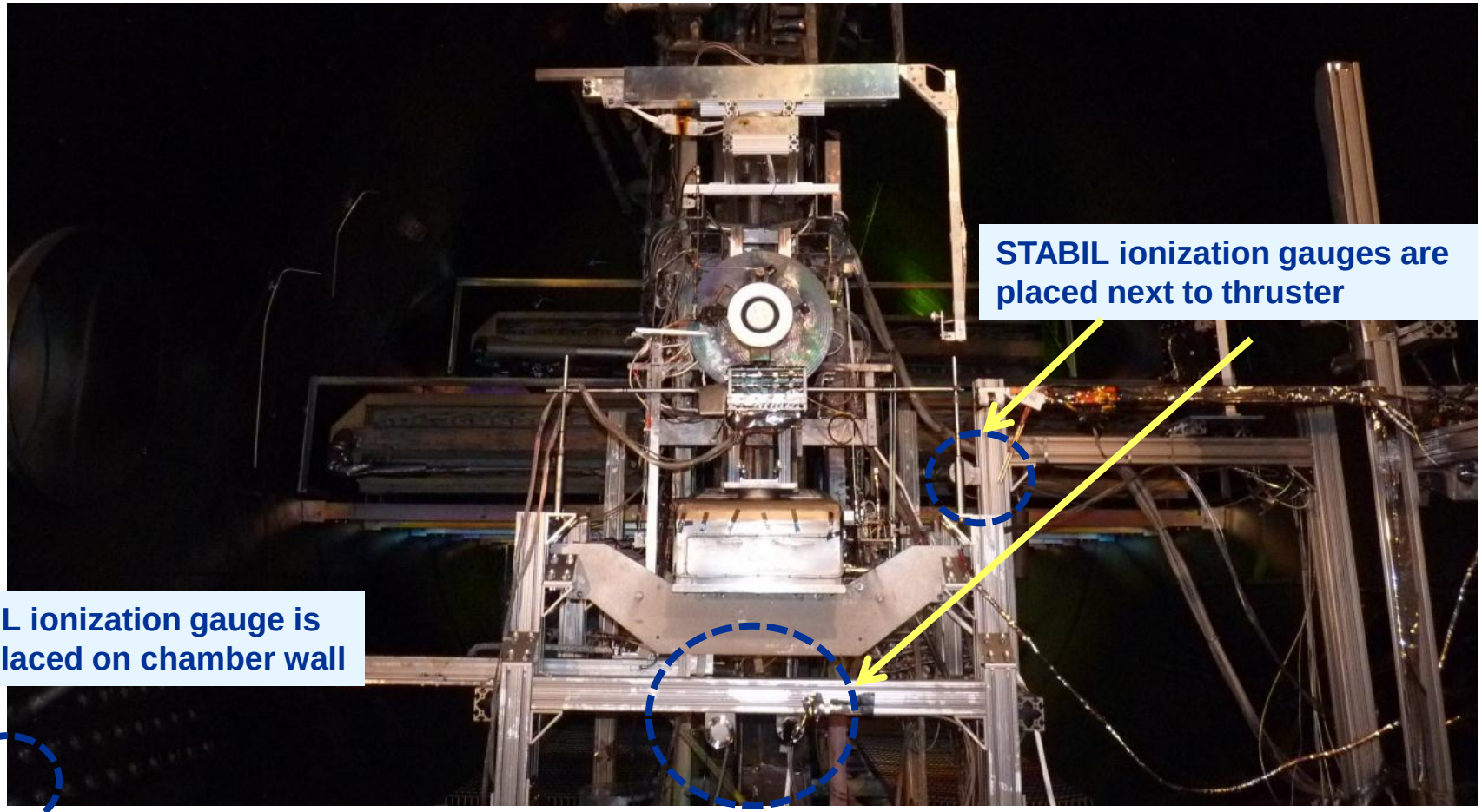
Single String Integration Test
Configuration in NASA Glenn Vacuum Facility 5 – (p4 of 5)



- Far field diagnostics includes an IR camera, fast camera, and plasma probes (EXB, RPA, LP)

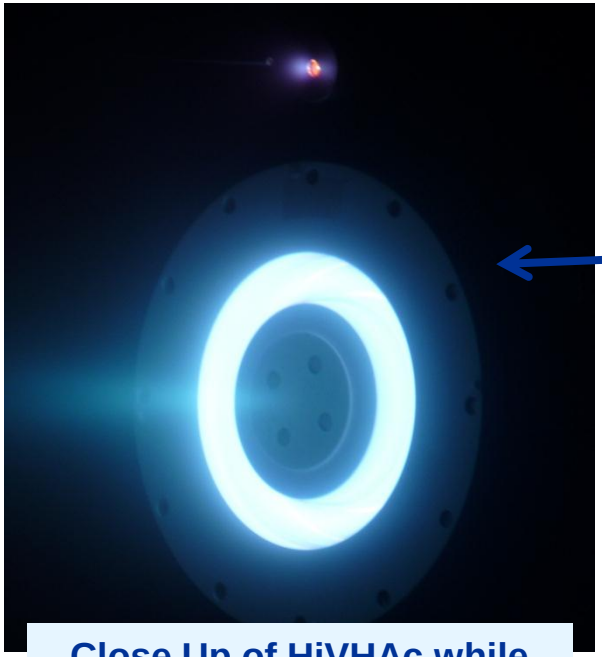
Single String Integration Test

Configuration in NASA Glenn Vacuum Facility 5 – (p5 of 5)

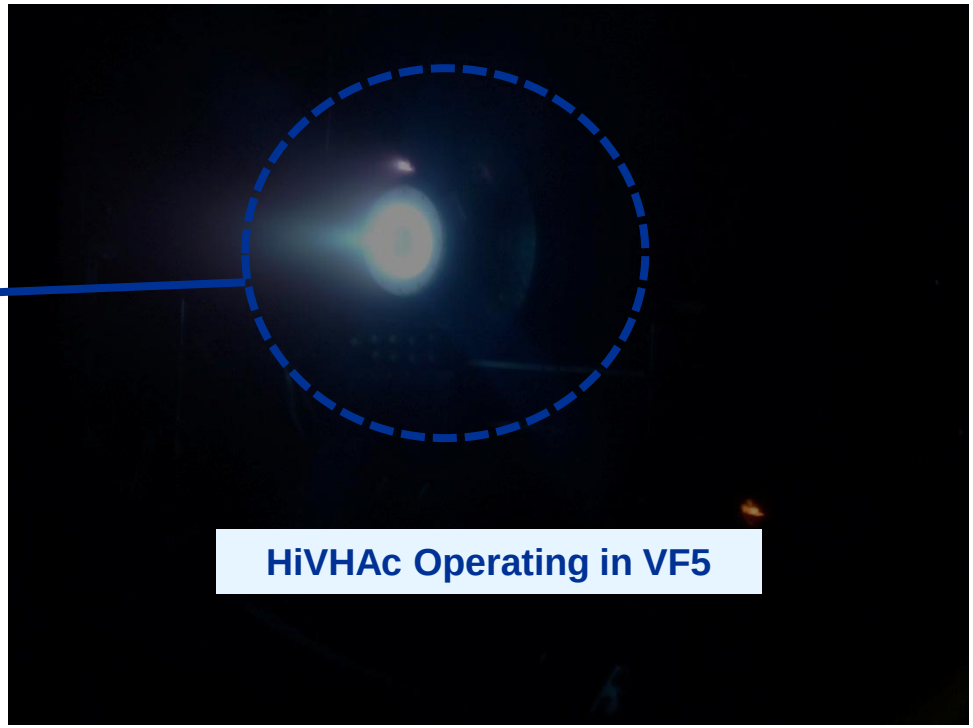


Single String Integration Test
Preliminary Test Results

- The HiVHAc EDU/CPE BB PPU/VACCO XFCM SSIT has been performed in VF5
- Tests were performed at different background pressure operating conditions



Close Up of HiVHAc while operating inside VF5



HiVHAc Operating in VF5

Single String Integration Test
Preliminary Test Results

- Testing with the HiVHAc EDU/CPE BB PPU/VACCO XFCM has been performed
- Preliminary analysis of the test results indicates an thruster performance obtained from VACCO XFCM is identical when compared to tests with the laboratory xenon flow controllers

	Laboratory MFCs			VACCO XFCM		
Vd, V	Anode Flow Rate, mg/s	Id, A	Thrust, mN (normalized)	Anode Flow Rate, mg/s	Id, A	Thrust, mN (normalized)
600	2	1.82	1	2.01	2.01	1
600	3.92	3.7	1	3.93	3.93	1.01
600	4.93	4.74	1	4.93	4.93	1
600	6.03	5.97	1	6.04	6.04	1.01

Single String Integration Test
Performance Characterization of HiVHAc

- **Performance characterization of the HiVHAc thruster was performed for the proposed HiVHAc throttle table**

	Power, W								
Vd, V	300	500	1000	1500	2000	2500	3000	3500	3900
200	x	x	x	x					
300*	x	x	x	x					
400*			x	x	x	x	x		
500			x	x	x	x	x	x	x
600			x	x	x	x	x	x	x
650			x	x	x	x	x	x	x

- **VF5 tests will be repeated in VF12**

Single String Integration Test

Thruster Performance Comparison at Different Background Pressure Conditions

		Background Pressure ~1.2X10^{-6} Torr		Background Pressure ~3.6X10^{-6} Torr		Background Pressure ~1.02X10^{-5} Torr		Background Pressure ~2.7X10^{-5} Torr	
Vd, V	Anode Flow Rate, mg/s	Id, A	Thrust, mN (normalized)	Id, A	Thrust, mN (normalized)	Id, A	Thrust, mN (normalized)	Id, A	Thrust, mN (normalized)
300	6.02	5.48	1	5.7	1.08	5.83	1.15	6.23	1.24
400	6.02	5.87	1	5.99	1.05	6.06	1.13	6.61	1.2
500	6.02	5.87	1	5.97	1.05	6.6	1.1		
600	6.02	5.91	1	6.17	1.04				
650	6.02	6.02	1	6.53	1.03				

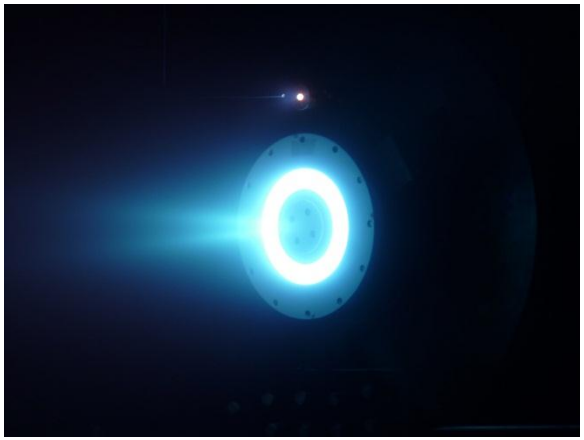
- Test results indicate that increased background pressure results in different thruster operation and performance
  - Increasing the background pressure resulted in increased discharge current and thrust at the same thruster operating conditions
- Further analysis of the thruster operating parameters, near-field FP, HSLP, FAST Camera, and far-field probe will be performed to elucidate observed trends

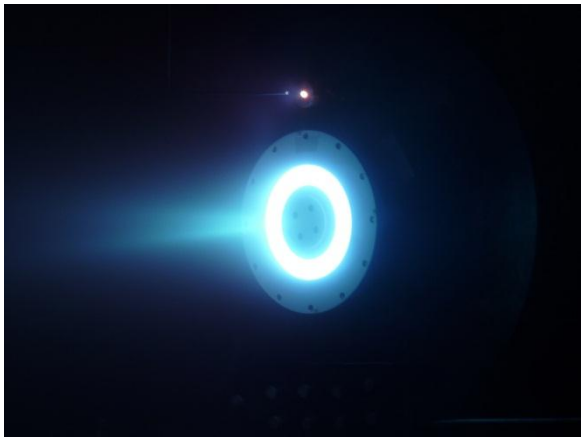
Single String Integration Test

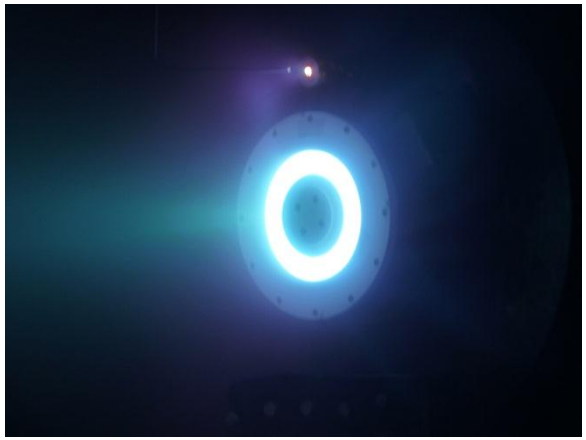
Thruster Performance Comparison at Different Background Pressure Conditions

Thruster Operating at 400 V and 6 mg/s

3x Pressure	10x Pressure	24x Pressure





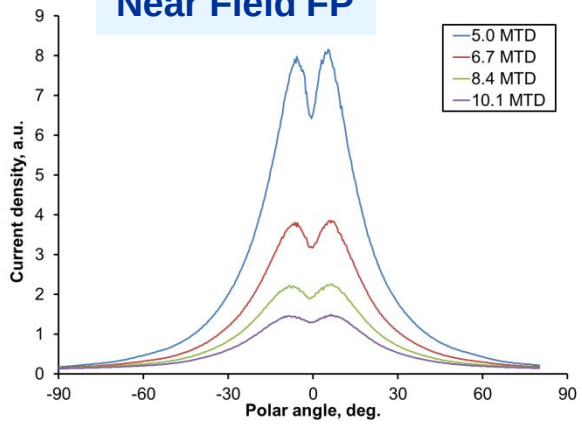


- Thruster plume structure changed as the background pressure was increased

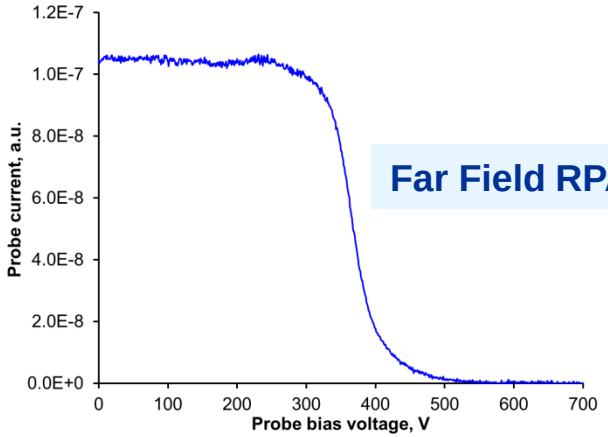
Single String Integration Test

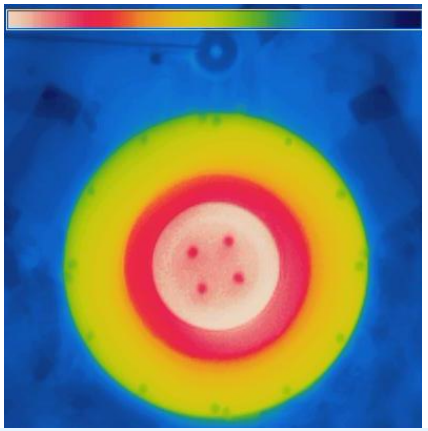
- **Analysis of the thermocouple, near field, HSLP, IR camera, Fast Camera, and far field plasma probes is ongoing**

Near Field FP



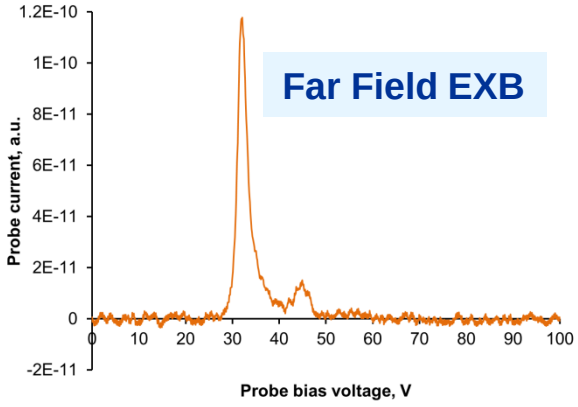
Far Field RPA



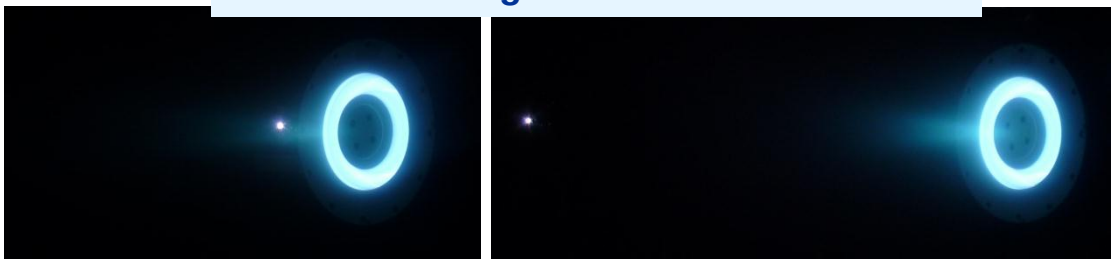


IR Camera Screen Capture at 3.9 kW

Far Field EXB



Thruster Testing with a Movable Cathode



Summary & Conclusions

- The HiVHAc Hall System components technology maturation task is ongoing
- The HiVHAc EDU thruster, which incorporates a movable life extension mechanism, has undergone extensive series of thruster performance and thermal characterization tests. The thruster has also survived random vibration test
- The HiVHAc CPE BB has undergone extensive testing and is being matured to TRL6. A Phase II & IIE SBIR projects are being leveraged to mature the CPE BB PPU to TRL5/6
- The VACCO XFCM is at TRL6
- The HiVHAc BB-level single string integration test incorporated an integrated test of the HiVHAc EDU 2 thruster, CPU BB PPU, and VACCO XFCM
- Preliminary test results in VF5 indicate an identical thruster performance with the CPE BB PPU and VACCO XFCM when compared to tests with laboratory power supplies and mass flow controllers

Acknowledgments

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